Ecological features of fast reactor nuclear power plants (NPPs) at all stages of their life cycle

O. Tashlykov[1], S. Sheklein[1], A. Sesekin[1] A. Chentsov[1], Y. Nosov[2] & O. Smyshlaeva[2]
[1]Ural Federal University, Russia
[2]Beloyarskaya NPP, Russia

Abstract

The future nuclear power industry should focus on the enhanced safety reactors such as inherently safe liquid metal fast neutron reactors.

Many years of the operating experience from the BN-600 fast power reactor show that it has some advantages in terms of safety (the large amount of sodium in the reactor, large boiling point margin, etc). The safety systems have been improved in BN-800 which is under construction and further in BN-1200 project.

Along with the design features of nuclear power plants, the overall safety culture including the optimization of radiation protection is very important.

The UrFU in conjunction with the Rosatom enterprises works in this direction, dealing with the route optimization of work in radiation fields using dynamic programming techniques, optimization of the composition of the homogeneous protective materials for a given isotopic composition of radioactive contamination, the development of computer models of radioactive systems for training of the dismantling personnel.

The management of the increasing amount of radioactive waste (RW) is the priority task of the nuclear power industry. Fast reactors allow it to minimize the amount of RW through the extraction of the fission products from the irradiated nuclear fuel while uranium and plutonium are returned to the reactor at a closed nuclear fuel cycle.
Keywords: nuclear power plant, fast breeder reactor, ecological management system, quality management system, safety, collective dose, closed nuclear fuel cycle.

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1 Role of the fast reactors in the solution of the nuclear power industry problems

A nuclear power plant (NPP), as well as other industrial and power facility has an impact on the environment, due to:

- technological heat discharges (thermal pollution),
- general industrial waste,
- discharges resulting from the operation of gaseous and liquid radioactive products.

The main feature of NPP process is the formation of considerable quantities of radioactive fission products being mainly in the fuel pins of the reactor core. For the reliable retention of radioactive products in the nuclear fuel and within the structural boundaries of the NPP a series of successive physical barriers on the way of the spread of radioactive substances and ionizing radiation into the environment is provided.

The important characteristic of the safety of a nuclear power plant is the limitation of its possible effect on the general public in case of an accident. As the safety requirements become more stringent the dimensions of the area of the possible evacuation of the general public are minimized. For new generation NPPs the objective is set to completely eliminate the need to evacuate the general public in the area of the location of the nuclear plant in case of any feasible accidents [1].

Currently, the world nuclear power industry is based on the pressurized water (thermal) nuclear reactors with the low efficiency of use of the energy potential of natural uranium. Therefore, the prospect of nuclear power development is reasonably associated today with the nuclear technology based on the fast reactors and closed nuclear fuel cycle (NFC). The reprocessing of spent nuclear fuel (SNF) and the return of the unused uranium and produced plutonium to the fuel cycle will allow about 100-fold increase in the energy potential of the fuel resources of the nuclear power industry. The unique physical properties of the fast reactors allow the long-lived nuclides of the radioactive waste of the nuclear power industry which complicate the solution of the problem of its disposal to be incinerated.

The liquid metal fast neutron reactors (compared to the pressurized water reactors) possess the following inherent safety features:

- the high coolant boiling point allows a low pressure in the reactor to be maintained,
- the absence of the phase transitions of the liquid metal coolants (LMC) in case of the loss of the reactor integrity contributes to maintaining a reliable core cooling,
- the low excess pressure of the cover gas of the liquid metal reactor.
- The sodium-cooled fast reactors possess the following additional properties of the inherent safety enhancing their safety:
- sodium effectively retains isotopes of iodine and cesium (which is confirmed by the operating experience from BN-600) which eliminates the release of the

dangerous isotopes of the gas-aerosol fraction of the fission products into the environment during normal operation and accidents,
- the weak corrosion-erosive effect of sodium on the structural materials eliminates the risk of overheating the fuel rods both due to the clogging of the flow cross section of the fuel sub-assemblies (S/A) and loss of integrity of the reactor vessel,
- good thermal and physical properties of sodium increase the efficiency of the heat removal and dissipation in emergency situations.

Beloyarsk NPP (BNPP) has unique experience in the operation and construction of the fast neutron power reactors.

BNPP unit No. 3 with the BN-600 fast neutron reactor of the rated electrical output of 600 MW has been put into operation on April 8, 1980, and is in operation. This is the only commercial fast reactor successfully operating for a so long time. During this period, the technology of safe handling of sodium was mastered and improved. The design service life of the unit was scheduled until 2010. On the basis of the accumulated operating experience, evaluation of the condition of the materials and upgrade and replacement of some equipment the license to operate it until 2020 with the right of further extension was obtained [2].

At the end of 2013, it is planned to obtain the first criticality of the BN-800 reactor (BNPP unit No. 4). At this power unit the problems related to the optimization of the closed NFC with the reuse of the generated transuranium elements and to the use of new types of high-density fuel to ensure high internal breeding in the next-generation reactors, new materials and new equipment designs having a higher reliability and a higher efficiency should be solved.

Currently unit No. 5 with a fast reactor of a larger power called BN-1200 or BN-K (fast, sodium, commercial) is designed. This will be the head commercial power unit intended for serial construction. It is supposed to have been built by 2025.

Thus, Beloyarsk NPP is the basis for the development of the sodium-cooled fast reactors. The accumulated experience allows it to summarize and analyze the ecological features of the reactors of this type at all the stages of the life cycle and to determine ways to improve safety.

2 Material and methods

2.1 Analysis of the Beloyarsk NPP influence on the environment

2.1.1 Thermal and chemical influence

The main types of non-radiological impact on the environment of Beloyarsk NPP are as follows: thermal impact, discharge of pollutants into water bodies, polluting emissions into the atmosphere and on-site waste storage.

At the nuclear power plant the steam turbine cycle which involves removal of a significant part of the heat released during the fission of nuclear fuel into the environment during steam condensation in the turbine condensers is used. The fast reactor power units have an efficiency of 41 to 42% (that of the thermal reactor NPPs ranges from 30 to 33%). Moreover, the heat is discharged to the environment with process water cooling a number of the NPP systems and equipment.

Thus, more than a half of the primary heat released in the fission of nuclear fuel in the reactor is dissipated in the atmosphere. Therefore, the issue of the recovery of low-grade heat discharged by the NPP is of interest both in terms of improving the efficiency and reducing the heat emissions. Currently, the department “Nuclear plants and renewable energy sources” of the UrFU has completed some work on evaluating the possibility of the recovery of the low-grade heat and reducing the heat emissions from the fast neutron reactor power units [3, 4].

The sources of the drinking water of BNPP are five wells of the Kamensky aquifer and one well of the Gagarsky aquifer. The source of process water is Beloyarsk reservoir. The water consumption limits established by the licenses are not exceeded.

In 2012, the effluents were discharged into the environment through four outlets (to Beloyarsk reservoir and to Olkhovskoye swamp). The effluents treated to standard quality after the oily waste treatment facilities are sent for reuse.

Quarterly the toxicological analyses of the wastewater in all the outlets, in Beloyarsk reservoir and river Olkhovka arising from Olkhovskoye swamp are carried out. The results of the analyses show the absence of toxicity in the samples taken.

In 2012, the air emissions amounted to 769.405 tons of pollutants (the standard of maximum allowable emissions is 1508 tons). The main sources of the emissions (more than 98% of the emissions from all the NPP sources) are boilers run on fuel oil.

The generation of the majority of the non-radioactive waste results both from the operation of the nuclear power plant auxiliary production facilities and replacement of the equipment with the expired lifetime. The NPP waste is similar to the waste generated at most industrial enterprises.

During the last few years the limits of the waste generation were exceeded only in 2010 for the waste of the fifth hazard class (scrap alloy steel and non-ferrous metals), i.e. actually non-hazardous waste. The overriding was caused by the large scope of work on the replacement of equipment in connection with the extension of the life of unit No. 3.

Beloyarsk NPP sends waste to specialist contractors for recovery and disposal.

2.1.2 Radiation impact

The actual emissions of the radioactive substances into the atmosphere from Beloyarsk NPP are mainly accounted for by the inert radioactive gases (IRG) and, as a rule, amount to less than one percent of the permissible value (fig. 1).

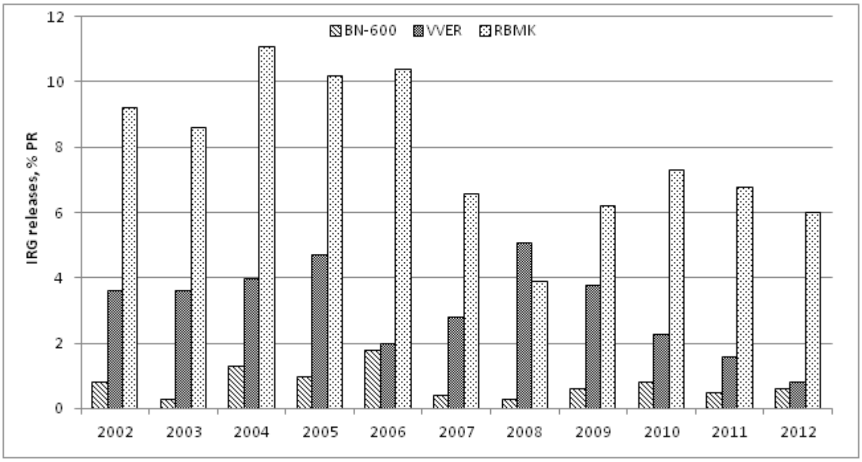

Figure 1: The release of the inert radioactive gases (% of the permissible release).

The radionuclide composition of water is determined by the spectrometric methods. Since 2000, under the TACIS project Russian NPPs have been supplied with the instruments for tritium monitoring in liquid media. Currently, most NPPs carry out the scheduled monitoring of tritium in water bodies (fig. 2).

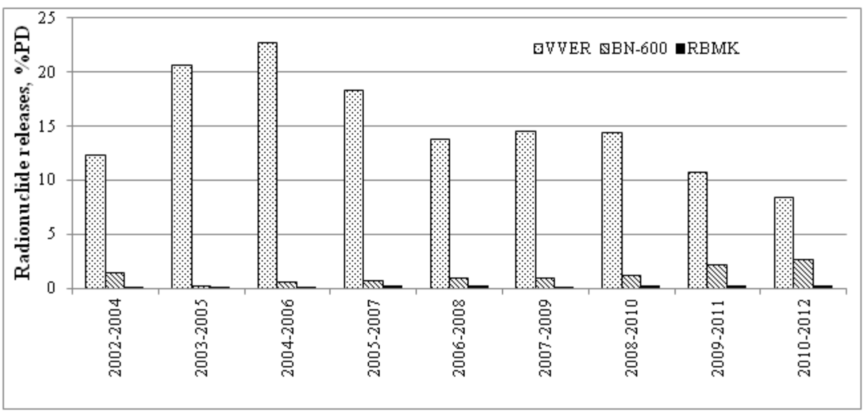

Figure 2: Change in the moving (for three consecutive years) averages of the discharges (percentage of the permissible discharge) of the radionuclides originated from the plant (with tritium) with unbalance water by the types of the reactors.

The systematic measurements of the concentration of radioactive substances in atmospheric air and cooling reservoirs as well as the measurements of the activity of the soil and vegetation and that of the food at the monitoring points confirm the absence of the influence of the NPP performance during normal operation on the state of the objects in the environment. At the same time the radiation risk for the general public living in the vicinity of Beloyarsk NPP is within the range of the unconditionally acceptable risk which does not require any additional measures to be taken to reduce the activity of radionuclides in the atmospheric and liquid discharges from nuclear power plants.

The complex of the “dry” waste storage is located within the NPP territory inside the guarded perimeter and is designed for storage of solid radioactive waste (SRW). The storages correspond to the standing regulations for the long-term bulk storage of the non-conditioned SRW. The technical condition of the liquid waste storage equipment corresponds to the design specifications and meets the requirements of the operational documentation.

The problems common for all the countries with the nuclear power industry are spent nuclear fuel and radioactive waste. NPPs exist and continue to be built in many countries, but only the lesser part of them plans to close the nuclear fuel cycle and for this purpose to build fast reactors. In comparison to these countries, since the Soviet Union Russia has created an advantage of 15 to 20 years in terms of the fast reactors. The concept of the fast reactor is based on the possibility of minimizing the volume of HLW (actually only the volume of the fission products) by extracting them from spent fuel and returning uranium and plutonium to the reactor.

2.2 Quality management system and environmental management system

The compliance with the required level of safety, reliability and efficiency of nuclear power plant operation is assured by the quality assurance system which functions at BNPP in accordance with the standing safety codes in the field of the nuclear power utilization.

The main objectives of the industrial environmental monitoring are as follows: to obtain the reliable estimate of NPP impact on the environment, to predict the development, to prevent emergency situations of the ecological nature, to justify and optimize the scope of the performed observations over the sources of the anthropogenic impact on and pollution of the environment taking into account the specific conditions both of the NPP location and state of environment.

The radiation monitoring of the objects in the environment within the control area and surveillance area is conducted by the off-site radiation monitoring group which is a part of the BNPP radiation safety department. In addition the monitoring of the state of environment is conducted on the basis of the results of the long-term observation. The trends in the parameters of the monitored objects are followed.

The automated radiation monitoring system (ARMS) is designed for the continuous measurement of gamma radiation dose rates and temperatures at the specified points of the site, control area and surveillance area of Beloyarsk NPP. The measurement results are transmitted via the radio channel to the Crisis Center of JSC “Concern Rosenergoatom” and “Rosatom” Corporation’s Crisis Management Center.

The objects of the monitoring of the BNPP's non-radioactive impact on environment are surface water objects, ground water, atmospheric air on the border of the residential area and polluting sources.

3 Results and their discussion

According to the State Report "On the condition of the environment and impact of the human environment factors on the health of the Sverdlovsk region general public" issued by the Ministry of Natural Resources of the Sverdlovsk region the BNPP's contribution to the gross amount of the atmospheric and liquid discharges is at the level of the basis points.

The only region in the vicinity of BNPP where the monitored parameters of the environmental radiation are above the background values is 0.47 km^2 Olkhovskoye swamp where unbalance water was discharged from power units 1 and 2 until 1980 (until the startup of BN- 600). These discharges and then poor sanitary limitation led to the accumulation of radionuclides lodged in the peat bog deposits. Now the inventory of the accumulated activity of ^{137}Cs and ^{60}Co in the swamp bottom silt is about $(2.0 \pm 0.6) \cdot 10^{11}$ Bq and $(2.4 \pm 0.8) \cdot 10^{9}$ Bq respectively. The sewage effluents are discharge to the swamp from the treatment plant of the BNPP site. The swamp is an alienated territory and is included to the Beloyarsk NPP control area.

Many years of the investigation of the radiation condition of Olkhovskoye swamp show that it is stable and its restoration is not required. The continuous monitoring of the state of the swamp, water activity and bottom silt is conducted. In 2007, to ensure the stability of Olkhovskoye swamp as a natural barrier on the way of the carry-over of radionuclides to the open hydrographic river system a bypass outfall sewer for the effluents from Zarechny treatment plant was built, bypassing the swamp, by the recommendation of the earlier conducted state environmental review and public independent examination.

These protective measures stopped degradation of Olkhovskoye swamp caused by the increasing effluents from Zarechny treatment plant. The vegetation typical for the marshy soil was restored. The beaver colonies appeared in Olhovskoe swamp and fish in Olhovka estuary. This indicates the improvement of the ecological state of the swamp and river system and adaptation of flora and fauna to the anthropogenic impact occurred earlier.

The BNPP waste water does not affect the Beloyarsk reservoir water quality.

For BN-600 power reactor unit some of the lowest dose levels both in Russia and in the world were achieved (figures 3 and 4). At the same time the repairs account for 50 to 75% of the collective dose. The exception is 1998 when over 182 days the extensive work was in hand to repair the central rotating column of the reactor [5].

When extending the operating life of BN-600, a series of activities aimed at improving safety were carried out. A part of this work was performed under conditions of exposure to ionizing radiation (fig. 5).

The total exposure caused by the work on the lifetime extension for the period of 2005 to 2010 is much lower than for the RBMK and VVER type reactors [6].

This is largely contributed by the pool arrangement of the BN-600 reactor with the main primary components enclosed in the reactor vessel. An exception is the primary sodium purification system of which equipment is located outside the reactor vessel.

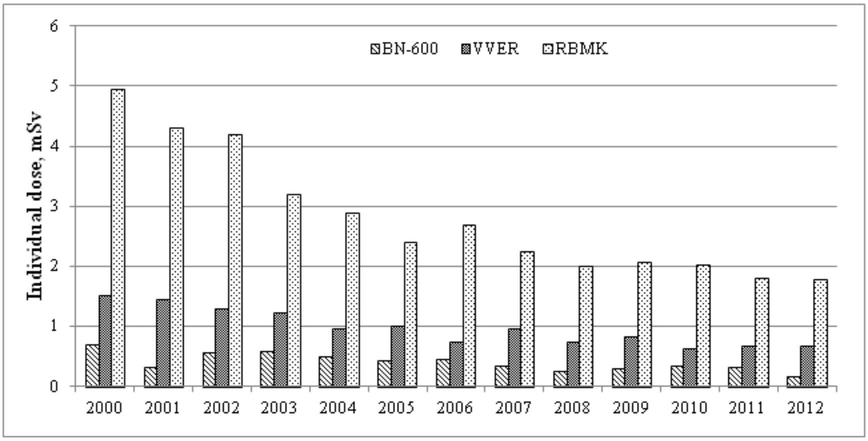

Figure 3: Weighted average individual exposure doses at Russian NPPs by reactor types.

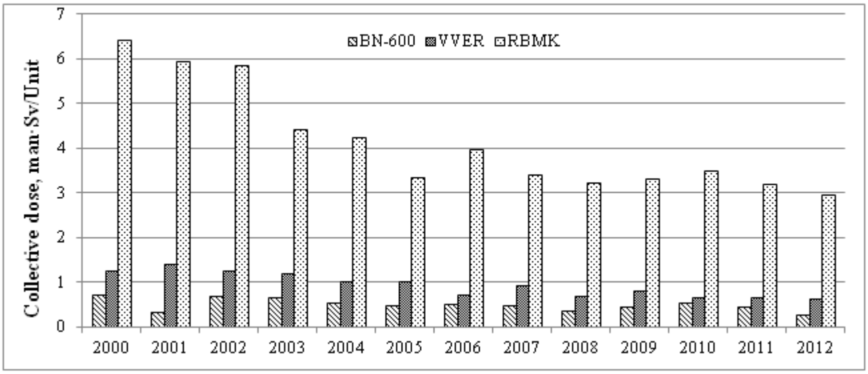

Figure 4: Collective exposure doses at Russian RBMK, VVER and BN-600 reactor nuclear power plant units

The collective dose reduction in 2012 is caused by the completion of work on extending the life of the unit No. 3.

The screening is the most common way to protect against ionizing radiation. The absorbing ability of the protective material depends on the γ-radiation spectrum (isotopic composition) of the radioactive contamination. Therefore, for the optimization of radiation protection the selection of the shielding material composition ensuring the necessary degree of the attenuation at minimum cost is important.

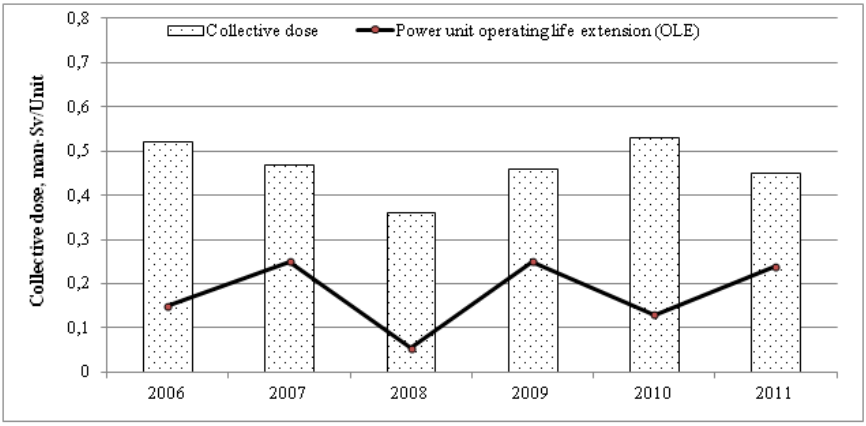

Figure 5: Contribution of the work on the extension of the BN-600 lifetime to the collective dose.

The isotopic composition of the radioactive contamination for BN-600 is different from other types of the reactor systems [5]. The radioactivity of the deposits on the surfaces of the primary circuit pipelines and equipment washed with sodium is determined by isotope ^{54}Mn. The activity of other radionuclides originated from corrosion (^{58}Co, ^{60}Co) and fission products (^{137}Cs, ^{134}Cs, ^{95}Nb, ^{140}La) on such surfaces is one or more factors less. On the surfaces of the cover gas chamber the ^{137}Cs deposits are prevailing (fig. 6).

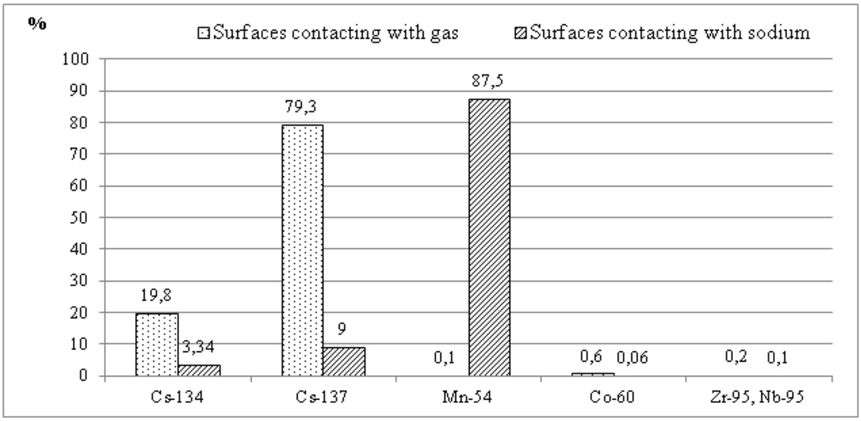

Figure 6: Contribution of individual radionuclides to the surface activity of the deposits on the removable part of the primary sodium pump.

In recent years, the UrFU experts jointly with the Institute of Reactor Materials (Zarechny) conducted a series of computational and experimental studies to design the composition of the homogeneous radiation protective materials of the "Абрис" type for the specific isotopic composition of contamination. The technology of the manufacturing of the homogeneous protective materials allows the necessary composition of the fillers having given attenuating properties to be created.

Design of the composition of a homogeneous protective material with the specified protective attenuating properties with respect to γ-radiation has a significant potential in the implementation of the principle of optimization of radiation protection.

4 Problems of the decommissioning

At present Beloyarsk NPP units Nos. 1 and 2 are under decommissioning (eventually shut down in 1983 and 1989). Decommissioning is a long, complex, and expensive process potentially dangerous for personnel, general public and environment. To reduce costs and improve security and to optimize the process of decommissioning a preliminary computer simulation must conducted.

Currently, the department "Nuclear power plants and renewable energy sources" of the UrFU works on the preparation of the work performance projects related to the dismantling of the equipment of the decommissioned NPP power units. At the same time the particular attention is paid to the training of personnel, including the training in the development of the 3D-models of the systems to be dismantled. The developed models allow one to study the layout of the equipment, obtain the necessary information on the types of compounds and materials and plan the sequence of dismantling of the individual elements of pipelines and equipment. The computer models have a built-in photo library that allows the separate components and their environment to be studied.

The training using the computer models allows an employee to reduce the time of the work in the radiation hazardous area and to decrease the exposure.

Another effective way to reduce personnel exposure that does not require significant material expenses is a route optimization of the work in radiation fields. The computational programs using the dynamic programming techniques developed in the UrFU allow the personnel exposure during dismantling to be minimized [7–9].

5 Use of Beloyarsk NPP's experience for the design of advanced reactors

BN1200's design is related to the reactors of enhanced safety due to the optimal combination of reference and new solutions, assurance of high safety indicators and high technical and economic features, and also due to the possibility of expanded breeding.

The probability of severe core damage at BN1200 is ten times less that it is required in regulatory documents; the control area is within the site boundaries for any design basis accident [1].

The concept of the designed BN1200 power unit is based on the significant positive experience of the development and operation of sodium fast reactors and the maximum possible use of the achievements of this technology.

The BN1200's design envisages the increased level of radiation and fire safety. All the systems with radioactive sodium are placed within the reactor vessel, which excludes the possibility of radioactive sodium release into the reactor premises through the external communications.

The length of the secondary sodium pipelines is reduced almost three times as compared with BN800's ones due to transition to a shell type steam generator and application of bellows expansion joints. All the pipelines will have guard covers. This eliminates large leaks and fires of non-radioactive sodium.

By now the environmental protection requirements have become more stringent. It is prohibited to use once-through systems and reservoirs constructed on rivers as cooling ponds for the newly designed thermal and nuclear power plants. Therefore the adopted for BN1200 process water supply system is a reverse one, where a high-capacity chimney type cooling tower is used for process water cooling.

The experience of BN800 construction in the modern context with new technologies, materials and construction mechanisms is extremely useful for the design of commercial BN1200 and will be used in its construction.

6 Conclusions

1. The main condition for the existence of the nuclear power engineering is nuclear safety assurance at all stages of a NPP's life cycle.
2. A continuous operation of BN600 power unit with a fast neutron reactor shows the absence of damage effect on the environment and population health. This reactor is recognized as one of the cleanest in the world.
3. The accumulated experience in the development and operation of sodium fast reactors shows the effectiveness of solutions built into BN600's design, high levels of reliability and safety. These solutions have been further developed in the designs of BN800 and BN1200.
4. The power units with fast reactors are the backbone elements of the closed nuclear fuel cycle, which makes it possible to minimize the amount of radioactive waste and to increase significantly the fuel potential of nuclear power engineering.

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